

Search for CP Violation in the Decay $D^+ \rightarrow K_S^0 K^+$

Belle Collaboration

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ABSTRACT:

We search for CP violation in the decay $D^+ \rightarrow K_S^0 K^+$ using a data sample with an integrated luminosity of 977 fb^{-1} collected with the Belle detector at the KEKB e^+e^- asymmetric-energy collider. No CP violation has been observed and the CP asymmetry in $D^+ \rightarrow K_S^0 K^+$ decay is measured to be $(-0.25 \pm 0.28 \pm 0.14)\%$, which is the most sensitive measurement to date. After subtracting CP violation due to $K^0 - \bar{K}^0$ mixing, the CP asymmetry in $D^+ \rightarrow \bar{K}^0 K^+$ decay is found to be $(+0.08 \pm 0.28 \pm 0.14)\%$.

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1 Introduction

Studies of CP violation in charmed meson decays provide a promising opportunity to search for new physics beyond the standard model (SM) [1] in the absence of disagreement between experimental measurements and the SM interpretation of CP violation in K and B meson decays [2–4]. Recently, the LHCb collaboration has reported $\Delta A_{CP} = (-0.82 \pm 0.21 \pm 0.11)\%$ [5] where ΔA_{CP} is the CP asymmetry difference between $D^0 \rightarrow K^+ K^-$ ¹ and $D^0 \rightarrow \pi^+ \pi^-$ decays. Thereafter, the CDF collaboration has also announced $\Delta A_{CP} = (-0.62 \pm 0.21 \pm 0.10)\%$ [6], which strongly supports the non-zero ΔA_{CP} measured from the LHCb collaboration. Together with results from the BaBar and Belle collaborations, the value of ΔA_{CP} is significantly different from zero [7]. Taking into account that the indirect CP asymmetries in the two decays are approximately equal [8], ΔA_{CP} can be expressed as

$$\Delta A_{CP} = \Delta a_{CP}^{\text{dir}} + a_{CP}^{\text{ind}} \Delta \langle t \rangle / \tau, \quad (1.1)$$

where a_{CP}^{dir} and a_{CP}^{ind} denote direct and indirect CP violation, respectively, and $\langle t \rangle / \tau$ is the mean proper decay time of the selected signal sample in units of the D^0 lifetime [9]. The factor $\Delta \langle t \rangle / \tau$ in eq. (1.1) depends on the experimental conditions and the largest value reported to date is 0.26 ± 0.01 from the CDF measurement [6]. Therefore, ΔA_{CP} reveals a significant direct CP violation difference between the two decays. Within the SM, direct CP violation in the charm sector is expected to be present only in singly Cabibbo-suppressed (SCS) decays, and even there is expected to be small, $\mathcal{O}(0.1\%)$ [10]. Hence, the current ΔA_{CP} measurements engender questions of whether the origin of the asymmetry lies within [11–14] or beyond [15–18] the SM. The origin of ΔA_{CP} calls for the precise

¹Throughout this paper, the charge-conjugate decay modes are implied unless stated otherwise.

measurements of A_{CP} in $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ \pi^-$. A complementary test is a precise measurement of A_{CP} in another SCS charmed hadron decay, $D^+ \rightarrow \bar{K}^0 K^+$, as suggested in ref. [13]. As shown in figures 1(a) and 1(b), the decay $D^+ \rightarrow \bar{K}^0 K^+$ shares the same

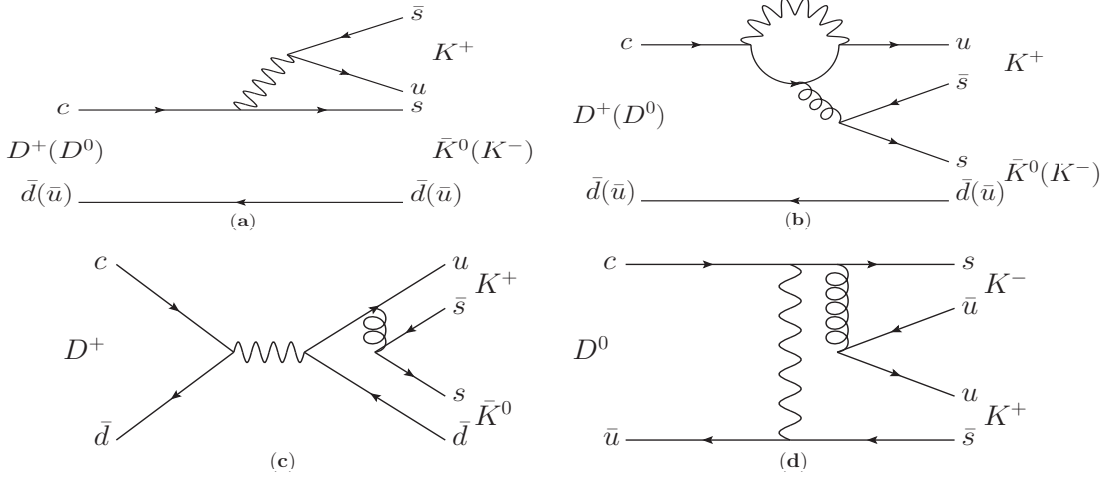


Figure 1. Feynman diagrams of $D^+ \rightarrow \bar{K}^0 K^+$ and $D^0 \rightarrow K^+ K^-$ decays.

decay diagrams with $D^0 \rightarrow K^+ K^-$ by exchanging the spectator quarks, $d \leftrightarrow u$. Although there are additional contributions to the two decays as shown in figures 1(c) and 1(d), these are expected to be small due to helicity- and color-suppression considerations². Therefore, neglecting the latter contributions in $D^+ \rightarrow \bar{K}^0 K^+$ and $D^0 \rightarrow K^+ K^-$ decays, the direct CP asymmetries in the two decays are expected to be the same.

In this paper, we report results from a search for CP violation in the decay $D^+ \rightarrow K_S^0 K^+$ that originates from $D^+ \rightarrow \bar{K}^0 K^+$ decay, where K_S^0 decays to $\pi^+ \pi^-$. The CP asymmetry in the decay, A_{CP} , is then defined as

$$\begin{aligned}
 A_{CP}^{D^+ \rightarrow K_S^0 K^+} &\equiv \frac{\Gamma(D^+ \rightarrow \bar{K}^0 K^+) \Gamma(\bar{K}^0 \rightarrow \pi^+ \pi^-) - \Gamma(D^- \rightarrow K^0 K^-) \Gamma(K^0 \rightarrow \pi^+ \pi^-)}{\Gamma(D^+ \rightarrow \bar{K}^0 K^+) \Gamma(\bar{K}^0 \rightarrow \pi^+ \pi^-) + \Gamma(D^- \rightarrow K^0 K^-) \Gamma(K^0 \rightarrow \pi^+ \pi^-)} \\
 &= \frac{A_{CP}^{D^+ \rightarrow \bar{K}^0 K^+} + A_{CP}^{\bar{K}^0}}{1 + A_{CP}^{D^+ \rightarrow \bar{K}^0 K^+} A_{CP}^{\bar{K}^0}} \simeq A_{CP}^{D^+ \rightarrow \bar{K}^0 K^+} + A_{CP}^{\bar{K}^0},
 \end{aligned} \tag{1.2}$$

where Γ is the partial decay width. In eq. (1.2), $A_{CP}^{D^+ \rightarrow \bar{K}^0 K^+}$ is the CP asymmetry in the decay $D^+ \rightarrow \bar{K}^0 K^+$ and $A_{CP}^{\bar{K}^0}$ is that in $\bar{K}^0 \rightarrow \pi^+ \pi^-$ decay induced by $K^0 - \bar{K}^0$ mixing in the SM [19–21] in which the decay $\bar{K}^0 \rightarrow \pi^+ \pi^-$ arises from $K_S^0 \rightarrow \pi^+ \pi^-$ together with a small contribution from $K_L^0 \rightarrow \pi^+ \pi^-$, where the latter is known precisely from K_L^0 semileptonic decays, $A_{CP}^{\bar{K}^0} = (-0.332 \pm 0.006)\%$ [2]. As shown in eq. (1.2), the product of the two small asymmetries is neglected. The D^+ decaying to the final state $K_S^0 K^+$ proceeds from $D^+ \rightarrow \bar{K}^0 K^+$ decay, which is SCS. In the SM, direct CP violation in SCS charmed meson decays is predicted to occur with a non-vanishing phase that enters the diagram

²In helicity suppression, a spinless meson decaying to a back-to-back quark-antiquark pair is suppressed by the conservation of angular momentum. In color suppression, the final state quarks are required to carry the correct color charge in order for the final state to be colorless.

shown in figure 1(b) in the Kobayashi-Maskawa ansatz [22]. The current average of ΔA_{CP} favors a negative value of direct CP violation in $D^0 \rightarrow K^+ K^-$ decay. Correspondingly, the CP asymmetry in $D^+ \rightarrow K_S^0 K^+$ decays is more likely to have a negative value since the two CP asymmetry terms shown in eq. (1.2) are negative.

2 Methodology

We determine $A_{CP}^{D^+ \rightarrow K_S^0 K^+}$ by measuring the asymmetry in the signal yield

$$A_{\text{rec}}^{D^+ \rightarrow K_S^0 K^+} = \frac{N_{\text{rec}}^{D^+ \rightarrow K_S^0 K^+} - N_{\text{rec}}^{D^- \rightarrow K_S^0 K^-}}{N_{\text{rec}}^{D^+ \rightarrow K_S^0 K^+} + N_{\text{rec}}^{D^- \rightarrow K_S^0 K^-}}, \quad (2.1)$$

where N_{rec} is the number of reconstructed decays. The asymmetry in eq. (2.1) includes the forward-backward asymmetry (A_{FB}) due to γ^*-Z^0 interference and higher order QED effects in $e^+e^- \rightarrow c\bar{c}$ [23–25], and the detection efficiency asymmetry between K^+ and K^- ($A_\epsilon^{K^+}$) as well as A_{CP} . In addition, ref. [26] calculates another asymmetry source, denoted $A_{\mathcal{D}}$, due to the differences in interactions of \bar{K}^0 and K^0 mesons with the material of the detector. Since we reconstruct the K_S^0 with $\pi^+\pi^-$ combinations, the $\pi^+\pi^-$ detection asymmetry cancels out for K_S^0 . The asymmetry of eq. (2.1) can be written as

$$A_{\text{rec}}^{D^+ \rightarrow K_S^0 K^+}(\cos \theta_{D^+}^{\text{c.m.s.}}, p_{TK^+}^{\text{lab}}, \cos \theta_{K^+}^{\text{lab}}, p_{K_S^0}^{\text{lab}}) = A_{CP}^{D^+ \rightarrow K_S^0 K^+} + A_{FB}^{D^+}(\cos \theta_{D^+}^{\text{c.m.s.}}) + A_\epsilon^{K^+}(p_{TK^+}^{\text{lab}}, \cos \theta_{K^+}^{\text{lab}}) + A_{\mathcal{D}}(p_{K_S^0}^{\text{lab}}) \quad (2.2)$$

by neglecting the terms involving the product of asymmetries. In eq. (2.2), $A_{CP}^{D^+ \rightarrow K_S^0 K^+}$ is the sum of $A_{CP}^{D^+ \rightarrow \bar{K}^0 K^+}$ and $A_{CP}^{\bar{K}^0}$ as stated in eq. (1.2), where the former is independent of all kinematic variables while the latter is known to depend on the K_S^0 decay time according to ref. [27], and $A_{FB}^{D^+}$ is an odd function of the cosine of the polar angle $\theta_{D^+}^{\text{c.m.s.}}$ of the D^+ momentum in the center-of-mass system (c.m.s.). $A_\epsilon^{K^+}$ depends on the transverse momentum $p_{TK^+}^{\text{lab}}$ and the polar angle $\theta_{K^+}^{\text{lab}}$ of the K^+ in the laboratory frame (lab). Here, $A_{\mathcal{D}}$ is a function of the lab momentum $p_{K_S^0}^{\text{lab}}$ of the K_S^0 . To correct for $A_\epsilon^{K^+}$ in eq. (2.2), we use the technique developed in our previous publication [28]. We use $D^0 \rightarrow K^- \pi^+$ and $D_s^+ \rightarrow \phi \pi^+$ decays where the ϕ is reconstructed with $K^+ K^-$ combinations and hence the $K^+ K^-$ detection asymmetry nearly cancels out [29] (the residual small effect is included in the systematic error). Since these are Cabibbo-favored decays for which the direct CP asymmetry is expected to be negligible, in analogy to eq. (2.2), $A_{\text{rec}}^{D^0 \rightarrow K^- \pi^+}$ and $A_{\text{rec}}^{D_s^+ \rightarrow \phi \pi^+}$ can be written as

$$A_{\text{rec}}^{D^0 \rightarrow K^- \pi^+}(\cos \theta_{D^0}^{\text{c.m.s.}}, p_{TK^-}^{\text{lab}}, \cos \theta_{K^-}^{\text{lab}}, p_{T\pi^+}^{\text{lab}}, \cos \theta_{\pi^+}^{\text{lab}}) = A_{FB}^{D^0}(\cos \theta_{D^0}^{\text{c.m.s.}}) + A_\epsilon^{K^-}(p_{TK^-}^{\text{lab}}, \cos \theta_{K^-}^{\text{lab}}) + A_\epsilon^{\pi^+}(p_{T\pi^+}^{\text{lab}}, \cos \theta_{\pi^+}^{\text{lab}}), \quad (2.3)$$

$$A_{\text{rec}}^{D_s^+ \rightarrow \phi \pi^+}(\cos \theta_{D_s^+}^{\text{c.m.s.}}, p_{T\pi^+}^{\text{lab}}, \cos \theta_{\pi^+}^{\text{lab}}) = A_{FB}^{D_s^+}(\cos \theta_{D_s^+}^{\text{c.m.s.}}) + A_\epsilon^{\pi^+}(p_{T\pi^+}^{\text{lab}}, \cos \theta_{\pi^+}^{\text{lab}}). \quad (2.4)$$

Thus, with the additional $A_\epsilon^{K^-}$ term in $A_{\text{rec}}^{D^0 \rightarrow K^- \pi^+}$, one can measure $A_\epsilon^{K^-}$ by subtracting $A_{\text{rec}}^{D_s^+ \rightarrow \phi \pi^+}$ from $A_{\text{rec}}^{D^0 \rightarrow K^- \pi^+}$, assuming the same A_{FB} for D^0 and D_s^+ mesons. We also obtain $A_{\mathcal{D}}$ according to ref. [26]. After these $A_\epsilon^{K^+}$ and $A_{\mathcal{D}}$ corrections³, we obtain

$$A_{\text{rec}}^{D^+ \rightarrow K_S^0 K_{\text{corr}}^+}(\cos \theta_{D^+}^{\text{c.m.s.}}) = A_{CP}^{D^+ \rightarrow K_S^0 K^+} + A_{FB}^{D^+}(\cos \theta_{D^+}^{\text{c.m.s.}}). \quad (2.5)$$

We subsequently extract A_{CP} and A_{FB} as a function of $\cos \theta_{D^+}^{\text{c.m.s.}}$ by taking sums and differences:

$$A_{CP}^{D^+ \rightarrow K_S^0 K^+}(|\cos \theta_{D^+}^{\text{c.m.s.}}|) = \frac{A_{\text{rec}}^{D^+ \rightarrow K_S^0 K_{\text{corr}}^+}(+\cos \theta_{D^+}^{\text{c.m.s.}}) + A_{\text{rec}}^{D^+ \rightarrow K_S^0 K_{\text{corr}}^+}(-\cos \theta_{D^+}^{\text{c.m.s.}})}{2}, \quad (2.6a)$$

$$A_{FB}^{D^+}(|\cos \theta_{D^+}^{\text{c.m.s.}}|) = \frac{A_{\text{rec}}^{D^+ \rightarrow K_S^0 K_{\text{corr}}^+}(+\cos \theta_{D^+}^{\text{c.m.s.}}) - A_{\text{rec}}^{D^+ \rightarrow K_S^0 K_{\text{corr}}^+}(-\cos \theta_{D^+}^{\text{c.m.s.}})}{2}. \quad (2.6b)$$

Note that extracting A_{CP} in eq. (2.5) using eq. (2.6a) is crucial here to cancel out the Belle detector's asymmetric acceptance in $\cos \theta_{D^+}^{\text{c.m.s.}}$.

3 Data and event selections

The data used in this analysis were recorded at the $\Upsilon(nS)$ resonances ($n = 1, 2, 3, 4, 5$) or near the $\Upsilon(4S)$ resonance with the Belle detector at the e^+e^- asymmetric-energy collider KEKB [30]. The data sample corresponds to an integrated luminosity of 977 fb^{-1} . The Belle detector is a large solid angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprising CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux return located outside the coil is instrumented to detect K_L^0 mesons and to identify muons. A detailed description of the Belle detector can be found in ref. [31].

Except for the tracks from K_S^0 decays we require charged tracks to originate from the vicinity of the interaction point (IP) by limiting the impact parameters along the beam direction (z -axis) and perpendicular to it to less than 4 cm and 2 cm, respectively. All charged tracks other than those from K_S^0 decays are identified as pions or kaons by requiring the ratio of particle identification likelihoods, $\mathcal{L}_K/(\mathcal{L}_K + \mathcal{L}_\pi)$, constructed using information from the CDC, TOF, and ACC, to be larger or smaller than 0.6, respectively [32]. For both kaons and pions, the efficiencies and misidentification probabilities are about 90% and 5%, respectively.

We form K_S^0 candidates adopting the standard Belle K_S^0 criteria [33], requiring the invariant mass of the charged track pair to be within $[0.4826, 0.5126] \text{ GeV}/c^2$. The “loose” K_S^0 candidates not satisfying these standard selections are also used in this analysis with additional requirements described later.

The K_S^0 and K^+ candidates are combined to form a D^+ candidate by fitting their tracks to a common vertex; the D^+ candidate is fitted to the independently measured IP

³We define $A^{h^+} \equiv [N^{h^+} - N^{h^-}]/[N^{h^+} + N^{h^-}]$. Hence $A^{h^-} = -A^{h^+}$.

profile to give the production vertex. To remove combinatorial background as well as D^+ mesons that are produced in possibly CP -violating B meson decays, we require the D^+ meson momentum calculated in the c.m.s. ($p_{D^+}^*$) to be greater than 2.5 and 3.0 GeV/ c for the data taken at the $\Upsilon(4S)$ and $\Upsilon(5S)$ resonances, respectively. For the data taken below $\Upsilon(4S)$, where no B mesons are produced, we apply the requirement $p_{D^+}^* > 2.0$ GeV/ c . In addition to the selections described above, we further optimize the signal sensitivity with four variables: the goodness-of-fit values of the D^+ decay- and production-vertex fits χ_D^2 and χ_P^2 , the transverse momentum of the K^+ in the lab $p_{TK^+}^{\text{lab}}$, and the angle ξ between the D^+ momentum vector (as reconstructed from its daughters) and the vector joining the D^+ production and decay vertices. We optimize the requirement on these four variables with the standard and loose K_S^0 selections by maximizing $\mathcal{N}_S/\sqrt{\mathcal{N}_S + \mathcal{N}_B}$, where $\mathcal{N}_S + \mathcal{N}_B$ and \mathcal{N}_B are the yields in the $K_S^0 K^+$ invariant mass signal ($[1.860, 1.884]$ GeV/ c^2) and sideband ($[1.843, 1.855]$ and $[1.889, 1.901]$ GeV/ c^2) regions, respectively. The optimal set of (χ_D^2 , χ_P^2 , $p_{TK^+}^{\text{lab}}$, ξ) requirements are found to be (<100 , <10 , >0.30 GeV/ c , $<40^\circ$), (<100 , <10 , >0.25 GeV/ c , $<115^\circ$), and (<100 , <10 , >0.20 GeV/ c , $<125^\circ$) for the data taken below the $\Upsilon(4S)$, at the $\Upsilon(4S)$, and at the $\Upsilon(5S)$, respectively. Note that $p_{D^+}^*$ is highly correlated with $p_{TK^+}^{\text{lab}}$ and ξ ; hence, a tighter $p_{D^+}^*$ requirement on the $\Upsilon(5S)$ sample results in looser $p_{TK^+}^{\text{lab}}$ and ξ requirements and vice versa for the data taken below the $\Upsilon(4S)$. The D^+ candidates with the loose K_S^0 requirement are further optimized with two additional variables: the χ^2 of the fit of tracks from the K_S^0 decay and the kaon from the D^+ meson decay to a single vertex (χ_{Khh}^2) and the angle ζ between the K_S^0 momentum vector (as reconstructed from its daughters) and the vector joining the D^+ and K_S^0 decay vertices. The two variables are again varied simultaneously and the optimum is found to be $\chi_{Khh}^2 > 6$ and $\zeta < 3^\circ$ for all data. The inclusion of D^+ candidates with the loose K_S^0 requirement improves the statistical sensitivity by approximately 5%. After the final selections described above, we find no significant peaking backgrounds—for example, $D^+ \rightarrow \pi^+ \pi^- K^+$ decays—in the Monte Carlo (MC) simulated events [34]. Figure 2 shows the distributions of $M(K_S^0 K^+)$ and $M(K_S^0 K^-)$ together with the results of the fits described below.

Each $D^\pm \rightarrow K_S^0 K^\pm$ signal is parameterized as two Gaussian distributions with a common mean. The combinatorial background is parameterized with the unnormalized form $e^{\alpha + \beta M(K_S^0 K^\pm)}$, where α and β are fit parameters. The asymmetry and the sum of the D^+ and D^- yields are directly obtained from a simultaneous fit to the D^+ and D^- candidate distributions. Besides the asymmetry and the sum of the D^+ and D^- yields, the common parameters in the simultaneous fit are the widths of the two Gaussians and the ratio of their amplitudes. The asymmetry and the sum of the $D^+ \rightarrow K_S^0 K^+$ and $D^- \rightarrow K_S^0 K^-$ yields from the fit are $(+0.048 \pm 0.275)\%$ and 276812 ± 1156 , respectively, where the errors are statistical.

In order to measure the CP asymmetry in $D^+ \rightarrow K_S^0 K^+$ decays, we must also reconstruct $D^0 \rightarrow K^- \pi^+$ and $D_s^+ \rightarrow \phi \pi^+$ decays: see eqs. (2.2), (2.3), and (2.4). For the reconstruction of the $D^0 \rightarrow K^- \pi^+$ and $D_s^+ \rightarrow \phi \pi^+$ decays, we require the same track quality, particle identification, vertex fit quality, and p_D^* requirements as used for the reconstruction of the $D^+ \rightarrow K_S^0 K^+$ decays, where the mass window for the ϕ is ± 16 MeV/ c^2 [29] of the nominal ϕ mass [2].

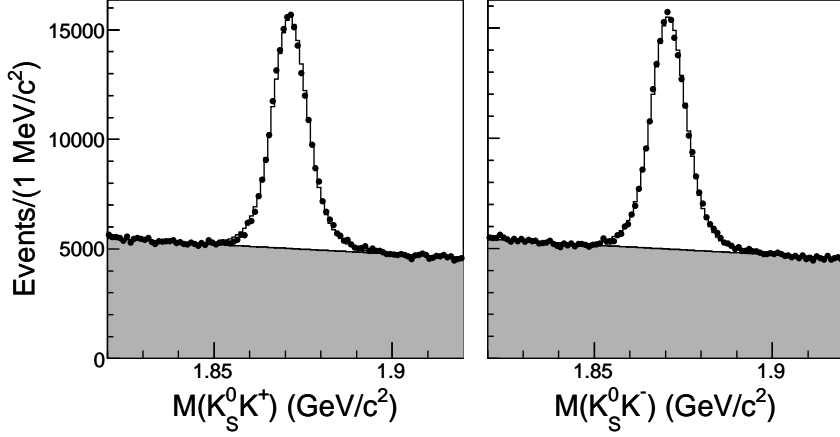


Figure 2. Distributions of $M(K_S^0 K^+)$ (left) and $M(K_S^0 K^-)$ (right). Dots are the data while the histograms show the results of the parameterizations of the data. Open histograms represent the $D^\pm \rightarrow K_S^0 K^\pm$ signal and shaded regions are combinatorial background.

4 Extraction of A_{CP} in the decay $D^+ \rightarrow K_S^0 K^+$

To obtain $A_\epsilon^{K^+}$, we first extract $A_{\text{rec}}^{D_s^+ \rightarrow \phi \pi^+}$ from a simultaneous fit to the mass distributions of D_s^+ and D_s^- candidates with similar parameterizations as for $D^\pm \rightarrow K_S^0 K^\pm$ decays except that, for the $D_s^\pm \rightarrow \phi \pi^\pm$ signal description, a single Gaussian is used. The values of $A_{\text{rec}}^{D_s^+ \rightarrow \phi \pi^+}$ are evaluated in $10 \times 10 \times 10$ bins of the three-dimensional (3D) phase space $(p_{T\pi^+}^{\text{lab}}, \cos \theta_{\pi^+}^{\text{lab}}, \cos \theta_{D_s^+}^{\text{c.m.s.}})$. Each $D^0 \rightarrow K^- \pi^+$ and $\bar{D}^0 \rightarrow K^+ \pi^-$ candidate is then weighted with a factor of $1 - A_{\text{rec}}^{D_s^+ \rightarrow \phi \pi^+}$ and $1 + A_{\text{rec}}^{D_s^+ \rightarrow \phi \pi^+}$, respectively, in the corresponding bin of this space. After this weighting, the asymmetry in the $D^0 \rightarrow K^- \pi^+$ decay sample becomes $A_\epsilon^{K^-}$. The detector asymmetry, $A_\epsilon^{K^-}$, is measured from simultaneous fits to the weighted $M(K^\mp \pi^\pm)$ distributions in 10×10 bins of the 2D phase space $(p_{TK^-}^{\text{lab}}, \cos \theta_{K^-}^{\text{lab}})$ with similar parameterizations as used for $D^+ \rightarrow K_S^0 K^+$ decays except that, for the $D^0 \rightarrow K^- \pi^+$ signal description, a sum of a Gaussian and bifurcated Gaussian is used. Figure 3 shows the measured $A_\epsilon^{K^-}$ in bins of $p_{TK^-}^{\text{lab}}$ and $\cos \theta_{K^-}^{\text{lab}}$ together with $A_{\text{rec}}^{D^0 \rightarrow K^- \pi^+}$ for comparison; we observe that $A_{\text{rec}}^{D^0 \rightarrow K^- \pi^+}$ shows a $\cos \theta_{K^-}^{\text{lab}}$ dependency that is inherited from $A_{FB}^{D^0}$ while $A_\epsilon^{K^-}$ does not. The average of $A_\epsilon^{K^-}$ over the phase space is $(-0.150 \pm 0.029)\%$, where the error is due to the limited statistics of the $D^0 \rightarrow K^- \pi^+$ sample.

Based on a recent study of A_D [26], we obtain the dilution asymmetry in bins of K_S^0 lab momentum. For the present analysis, A_D is approximately 0.1% after integrating over the phase space of the two-body decay.

The data samples shown in figure 2 are divided into $10 \times 10 \times 16$ bins of the 3D phase space $(p_{TK^+}^{\text{lab}}, \cos \theta_{K^+}^{\text{lab}}, p_{K_S^0}^{\text{lab}})$. Each $D^\pm \rightarrow K_S^0 K^\pm$ candidate is then weighted with a factor of $(1 \mp A_\epsilon^{K^\pm})(1 \mp A_D)$ in this space. The weighted $M(K_S^0 K^\pm)$ distributions in bins of $\cos \theta_{D^+}^{\text{c.m.s.}}$ are fitted simultaneously to obtain the corrected asymmetry. We fit the linear component in $\cos \theta_{D^+}^{\text{c.m.s.}}$ to determine A_{FB} ; the A_{CP} component is uniform in $\cos \theta_{D^+}^{\text{c.m.s.}}$. Figure 4 shows $A_{CP}^{D^+ \rightarrow K_S^0 K^+}$ and $A_{FB}^{D^+}$ as a function of $|\cos \theta_{D^+}^{\text{c.m.s.}}|$. From a weighted average

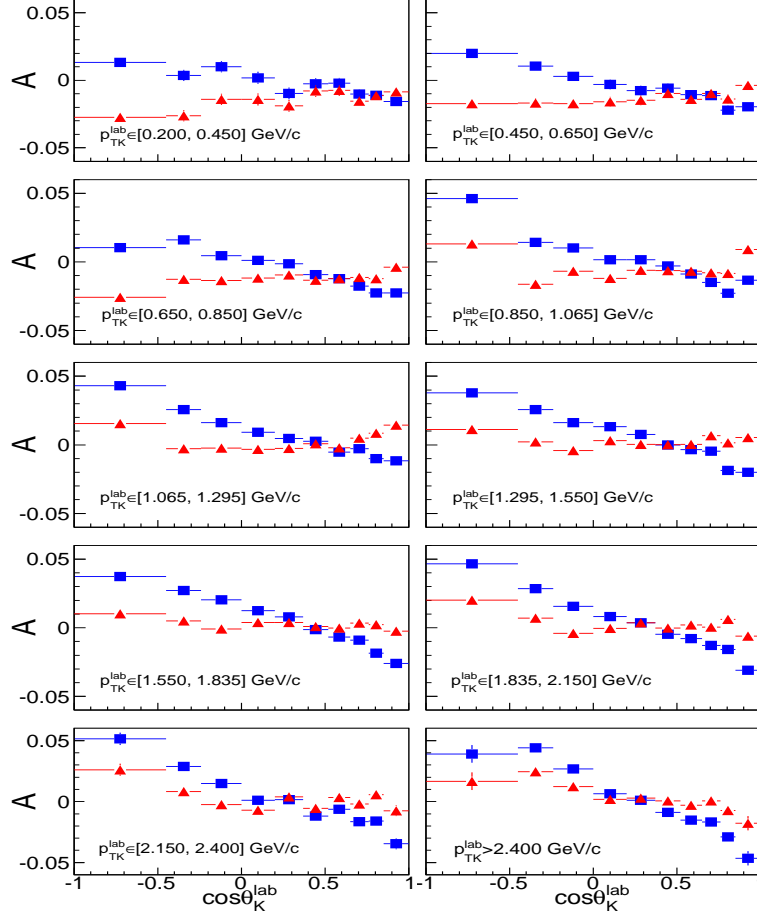


Figure 3. The $A_{\epsilon}^{K^-}$ map in bins of p_T^{lab} and $\cos \theta_K^{\text{lab}}$ of the K^- obtained with the $D^0 \rightarrow K^- \pi^+$ and $D_s^+ \rightarrow \phi \pi^+$ samples (triangles). The $A_{\text{rec}}^{D^0 \rightarrow K^- \pi^+}$ map is also shown (rectangles).

over the $|\cos \theta_{D^+}^{\text{c.m.s.}}|$ bins, we obtain $A_{CP}^{D^+ \rightarrow K_s^0 K^+} = (-0.246 \pm 0.275)\%$, where the error is statistical.

5 Systematic uncertainty

The entire analysis procedure is validated with fully simulated MC events [34] and the result is consistent with null input asymmetry. We also consider other sources of systematic uncertainty. The dominant one in the A_{CP} measurement is the $A_{\epsilon}^{K^+}$ determination, the uncertainty of which is mainly due to the statistical uncertainties in the $D^0 \rightarrow K^- \pi^+$ and $D_s^+ \rightarrow \phi \pi^+$ samples. These are found to be 0.029% and 0.119%, respectively, from a simplified simulation study. A possible A_{CP} in the $D^0 \rightarrow K^- \pi^+$ final state is estimated using $A_{CP} = -y \sin \delta \sin \phi \sqrt{R}$ [35]. A calculation with 95% upper and lower limits on $D^0 - \bar{D}^0$ mixing and CP violation parameters y , ϕ , and strong phase difference δ and Cabibbo suppression factor R from ref. [3], A_{CP} in the $D^0 \rightarrow K^- \pi^+$ final state is estimated to be less than 0.005% and this is included as one of systematic uncertainties in the $A_{\epsilon}^{K^+}$ determination. As reported in our previous publication [29], the magnitude of A_{rec}^{KK} for

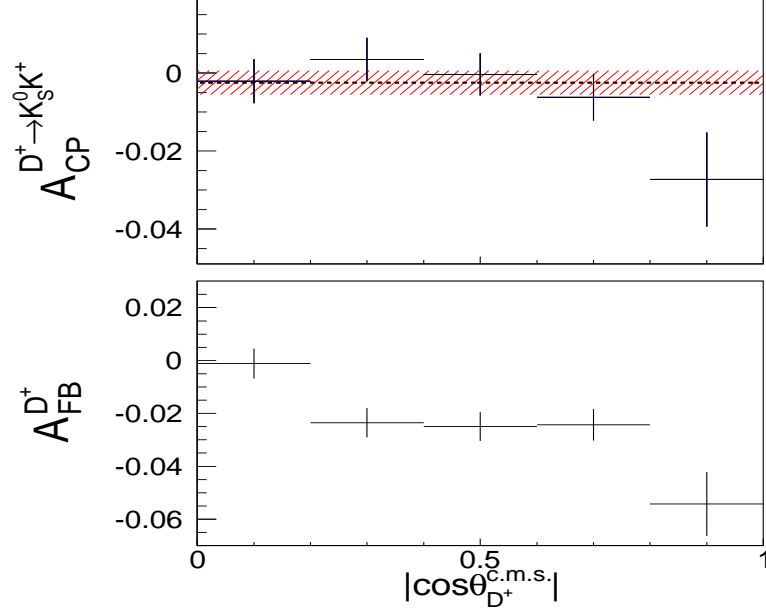


Figure 4. Measured A_{CP} (top) and A_{FB} (bottom) values as a function of $|\cos \theta_{D^+}^{c.m.s.}|$. In the top plot, the dashed line is the mean value of A_{CP} while the hatched band is the $\pm 1\sigma_{\text{total}}$ interval, where σ_{total} is the total uncertainty.

the ϕ reconstruction in $D_s^+ \rightarrow \phi \pi^+$ decays is 0.051%, which is also added to the systematic uncertainty in the $A_{\epsilon}^{K^+}$ measurement. By adding the contributions in quadrature, the systematic uncertainty in the $A_{\epsilon}^{K^+}$ determination is estimated to be 0.133%. We estimate 0.008% and 0.021% systematic uncertainties due to the choice of the fitting method and that of the $\cos \theta_{D^+}^{c.m.s.}$ binning, respectively. Finally, we add the systematic uncertainty in the A_D correction, which is 0.010% based on ref. [26]. The quadratic sum of the above uncertainties, 0.135%, is taken as the total systematic uncertainty.

6 Results

We find $A_{CP}^{D^+ \rightarrow K_S^0 K^+} = (-0.246 \pm 0.275 \pm 0.135)\%$. This measurement supersedes our previous determination of $A_{CP}^{D^+ \rightarrow K_S^0 K^+}$ [28]. In Table 1, we compare all the available measurements and give their weighted average.

According to Grossman and Nir [27], we can estimate the experimentally measured CP asymmetry induced by SM $K^0 - \bar{K}^0$ mixing, $A_{CP}^{\bar{K}^0}$. The efficiency as a function of K_S^0 decay time in our detector is obtained from MC simulated events. The efficiency is then used in eq. (2.10) of ref. [27] to obtain the correction factor that takes into account, for $A_{CP}^{\bar{K}^0}$, the dependence on the kaon decay time. The result is 0.987 ± 0.007 . By multiplying the correction factor 0.987 ± 0.007 and the asymmetry due to the neutral kaons [2], we find the experimentally measured $A_{CP}^{\bar{K}^0}$ to be $(-0.328 \pm 0.006)\%$.

Experiment	$A_{CP}^{D^+ \rightarrow K_S^0 K^+}$ (%)
FOCUS [36]	$+7.1 \pm 6.1 \pm 1.2$
CLEO [37]	$-0.2 \pm 1.5 \pm 0.9$
Belle (this measurement)	$-0.246 \pm 0.275 \pm 0.135$
New world average	-0.23 ± 0.30

Table 1. Summary of $A_{CP}^{D^+ \rightarrow K_S^0 K^+}$ measurements (where the first uncertainties are statistical and the second systematic), together with their average (assuming the uncertainties to be uncorrelated, the error on the average represents the total uncertainty).

7 Conclusion

We report the most sensitive CP asymmetry measurement to date for the decay $D^+ \rightarrow K_S^0 K^+$ using a data sample corresponding to an integrated luminosity of 977 fb^{-1} collected with the Belle detector. The CP asymmetry in the decay is measured to be $(-0.25 \pm 0.28 \pm 0.14)\%$. After subtracting the contribution due to $K^0 - \bar{K}^0$ mixing ($A_{CP}^{\bar{K}^0}$), the CP asymmetry in the charm decay ($A_{CP}^{D^+ \rightarrow \bar{K}^0 K^+}$) is measured to be $(+0.08 \pm 0.28 \pm 0.14)\%$, which can be compared with direct CP violation in $D^0 \rightarrow K^+ K^-$. For the latter the current averages of ΔA_{CP} and CP asymmetry in $D^0 \rightarrow K^+ K^-$ favor a negative value [3]. Our result, on the other hand, does not show this tendency for $D^+ \rightarrow \bar{K}^0 K^+$ decays, albeit with a significant statistical uncertainty.

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